Applying Fused Silica and Other Transparent Window Materials in Aerospace Applications

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Ceramic Expo, Cleveland, Ohio, April 26th, 2017

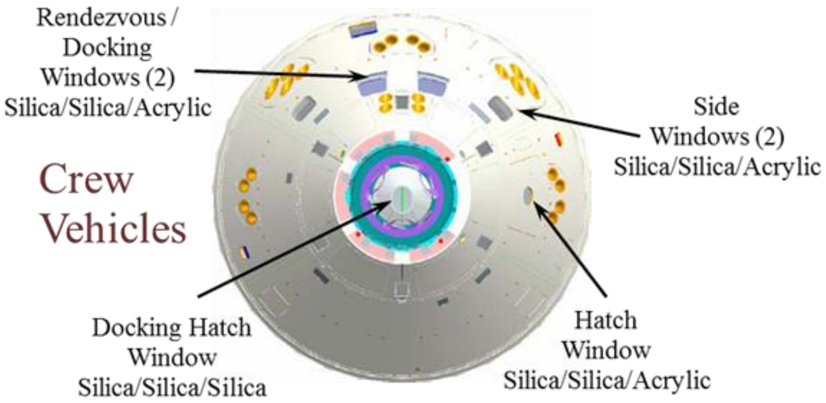
Conference @ceramics expo

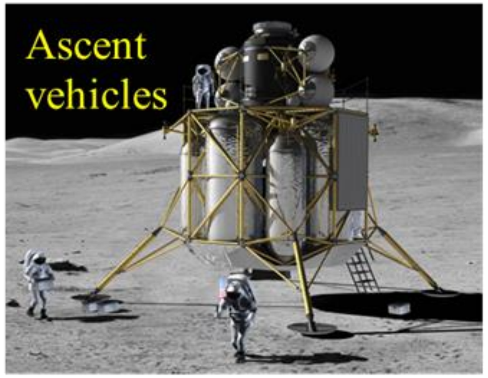
Outline

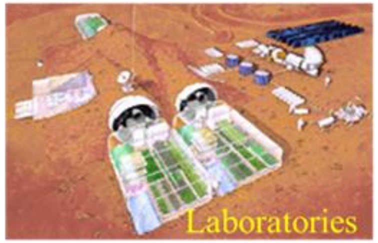
- Transparent Window Materials
  - Applications and the workhorse material
  - Newer materials
  - Application requirements
  - Emerging applications

- Design Guidelines for Structural Ceramic Components
  - Failure mechanisms, initiation sources and size effects
  - Design & Life prediction methods
  - Test methods - fracture mechanics & strength based
  - Example

Some Window Applications







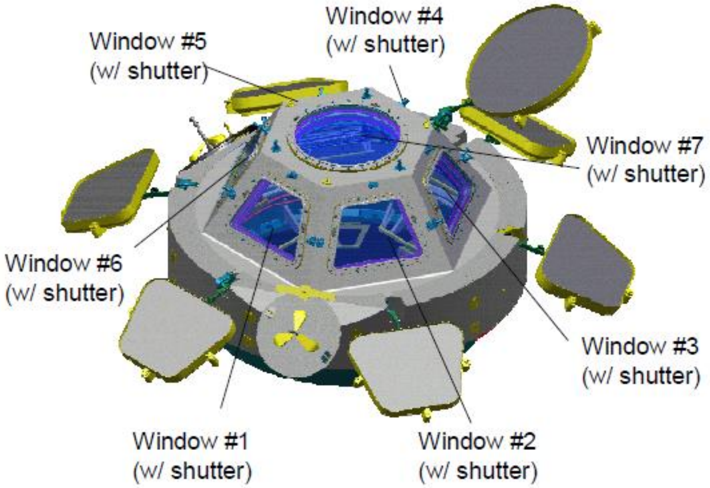
Workhorse Material – Fused Silica

- Fused silica has been the historical material of choice:
  - Apollo
  - SkyLab ('73-'74) , Mir…
  - ISS ('98-20xx)
  - Shuttle
  - Orion

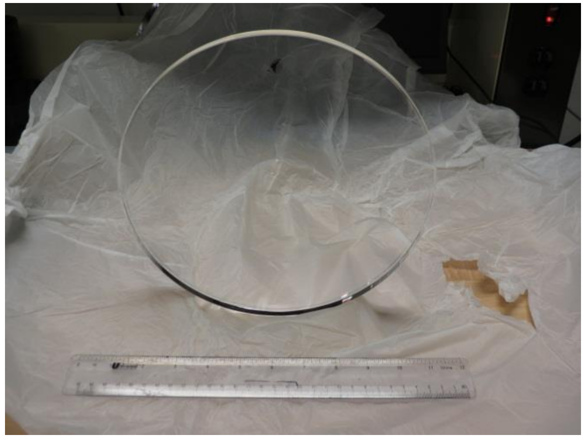
- Only one unexpected failure during an Apollo window proof test.
- "New" materials include spinels & AlON. Higher strength and fracture toughness.

Windows in Use - ISS

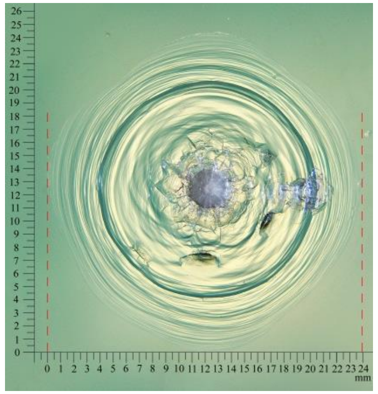
- Most famous are the Cupola windows, which are shuttered:



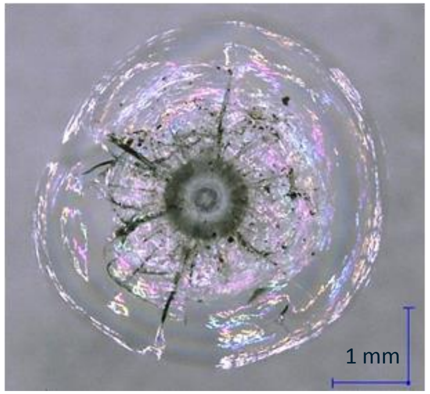
- More typical widow (10”ϕ):



HITF White Sands



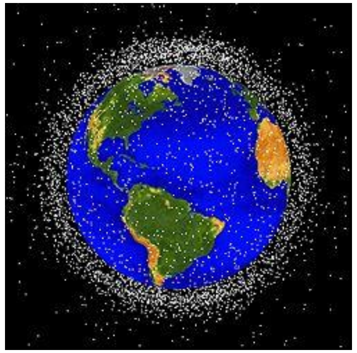
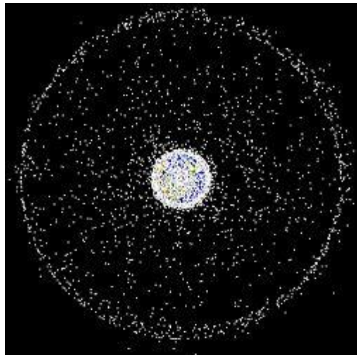
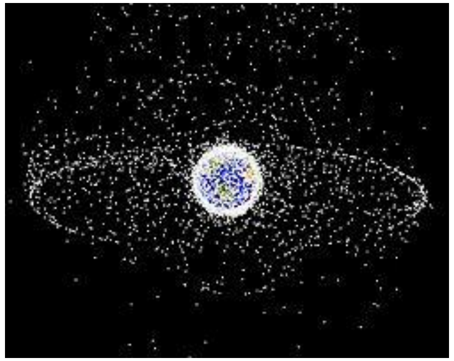
STS-84 Atlantis



- Some windows are not shuttered and can be damaged by MMOD….

Window Requirements

- Thermal shock – reentry; sun-shade cycle
- Structural/Mechanical – pressure (crack growth)
- Impact residual strength (handling, hyper)

- Optical (haze, transmittance…..imagery, piloting)
- Chemical (atomic oxygen, radiation..)

➢ Advantages of silica are optical and thermal.
➢ Disadvantage is low fracture toughness.
➢ But why windows at all?! Psychological & protection.

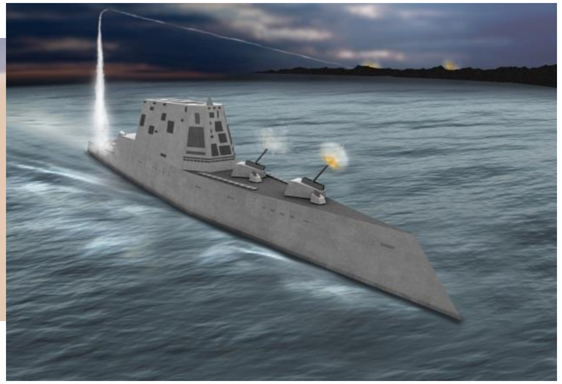
New, Impact Resistant Materials

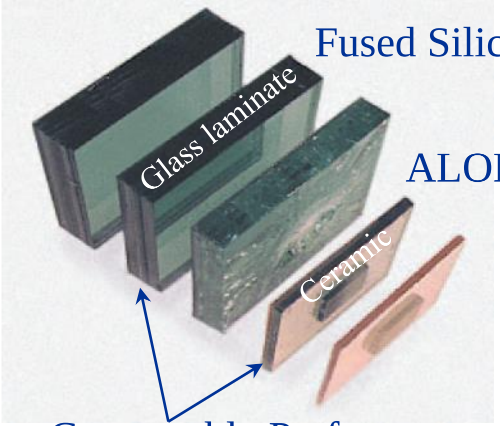
- A variety of "new" materials have been developed or re-developed:
  - AlON
  - Spinels
  - MgO, Alumina, glass-ceramics

19"

24"

- One driving force has been military armor:





- Might these materials work for spacecraft windows?

Characteristics of “New” Materials

- ALON and Spinels:

Material & Grain Size	Bulk Density g/cc	Young’s Modulus GPa	Fracture Toughness, MPa√m
Fused Silica	2.20	72	0.75
Spinel, 300 μm	3.57	265	1.6
110 μm	3.56	269	1.7
25 μm	-----	----	2.4
ALON, 220 μm	3.67	320	2.2

➢ Silica is “light” but very brittle.

Thermal Shock Resistance

- Thermal shock metric:

$$R'' = \frac{(1-\nu)\lambda\sigma_c}{\alpha E \rho C_p}$$

Material	Young's Modulus GPa	Fracture Strength (MPa)	CTE x $10^{-6}/^{o}C$ α	Thermal Conductivity (W/mK) λ	Heat Capacity (J/gK)	R” (Wcm^2/gK)
Silica	72	80	0.5	14	0.77	143
Spinel (coarse grain)	270	80	6	15	0.88	3.5
Spinel (fine grain)	270	160	6	15	0.88	3.5
AlON	320	210	5	13	0.92	3.8

- Positive: similar thermal conductivity.
- Negative: new materials have higher CTE & E.

➢ Poor thermal shock resistance…..

Structural/Mechanical Property Capability

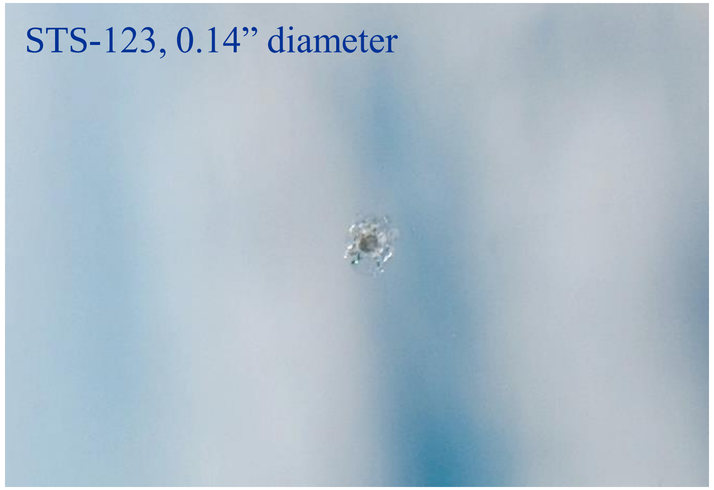
- Crack growth related:

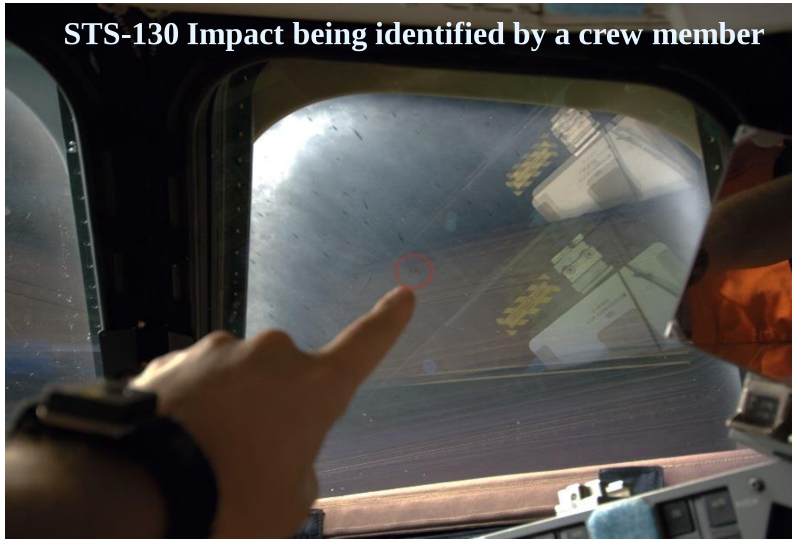
Material	Density (g/cc)	Young's Modulus (GPa)	Fracture Toughness (MPa√m)	Crack Growth Exponent, n	Fracture Strength MPa
Silica	2.2	72	0.75	24 - 40	80
Spinel (coarse grain)	3.6	270	1.6	22	80
Spinel (fine grain)	3.6	270	2.4	50	160
AlON	3.7	314	2.2	35 - 50	210

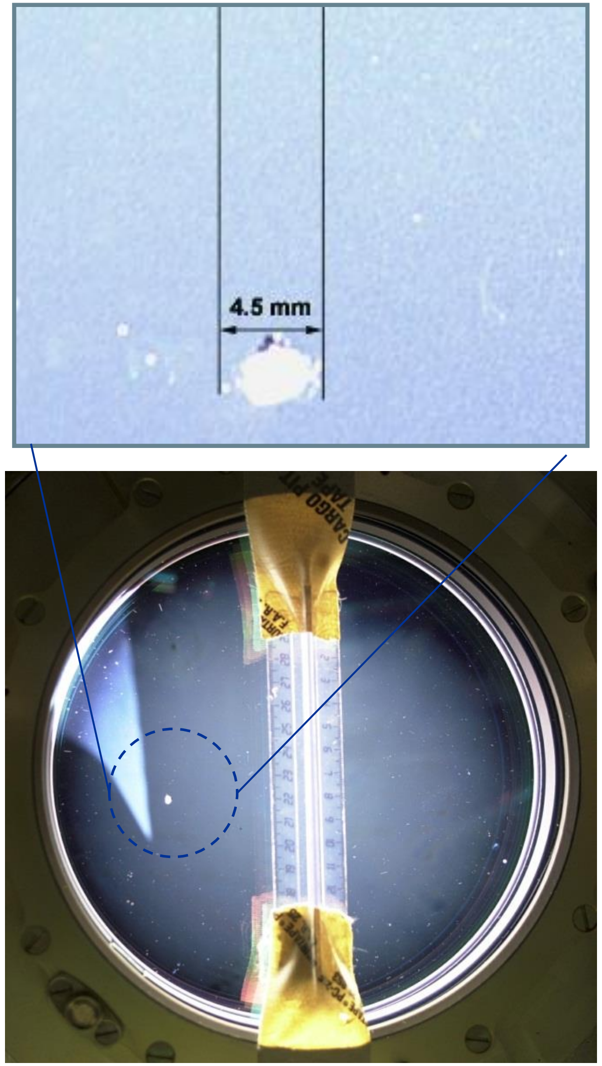
- Positive: New materials are tougher and SCG resistant.
- Negative: New materials are denser and stiffer.

➢ Better mechanical properties, but higher density.

Impact: Shuttle & Station Examples

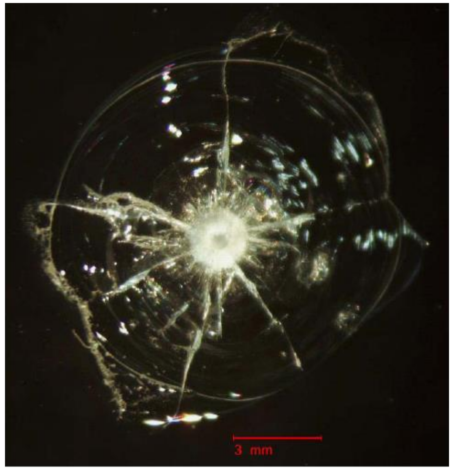

STS-123, 0.14” diameter

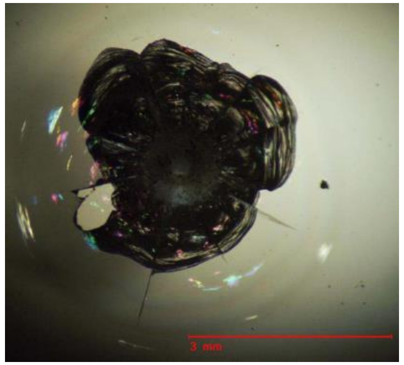

STS-130 Impact being identified by a crew member

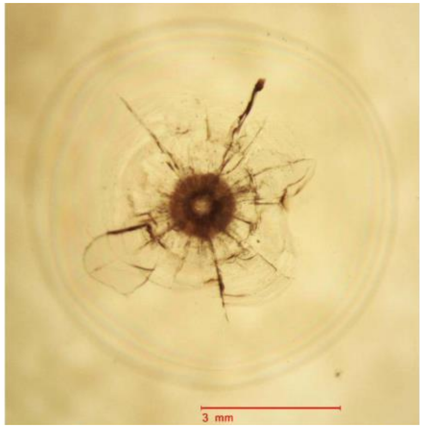


Hyper Velocity Impact of Spinel vs Silica

Silica

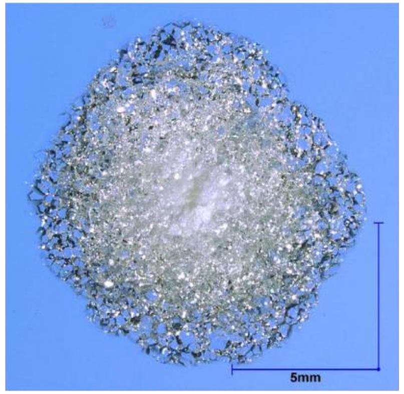


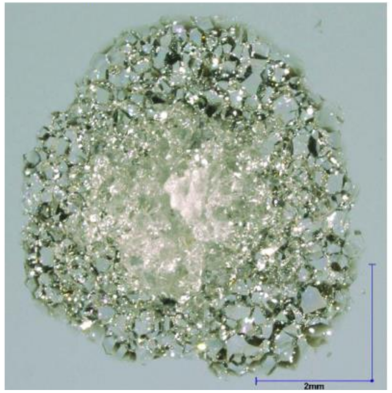


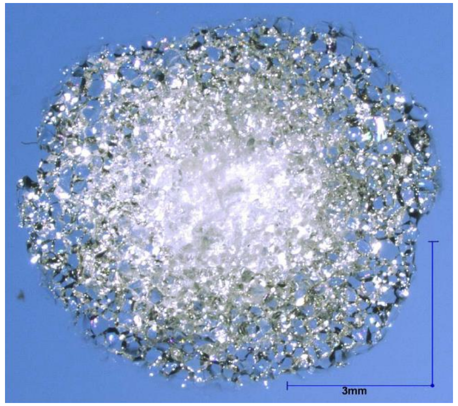


Central pit with radial and circumferential cracks.

Spinel







Large pit with gain boundary cracking.

- Similar sizes, but very different morphologies. Testing on-going.

Optical Properties & Emerging Applications

- Phone screens:

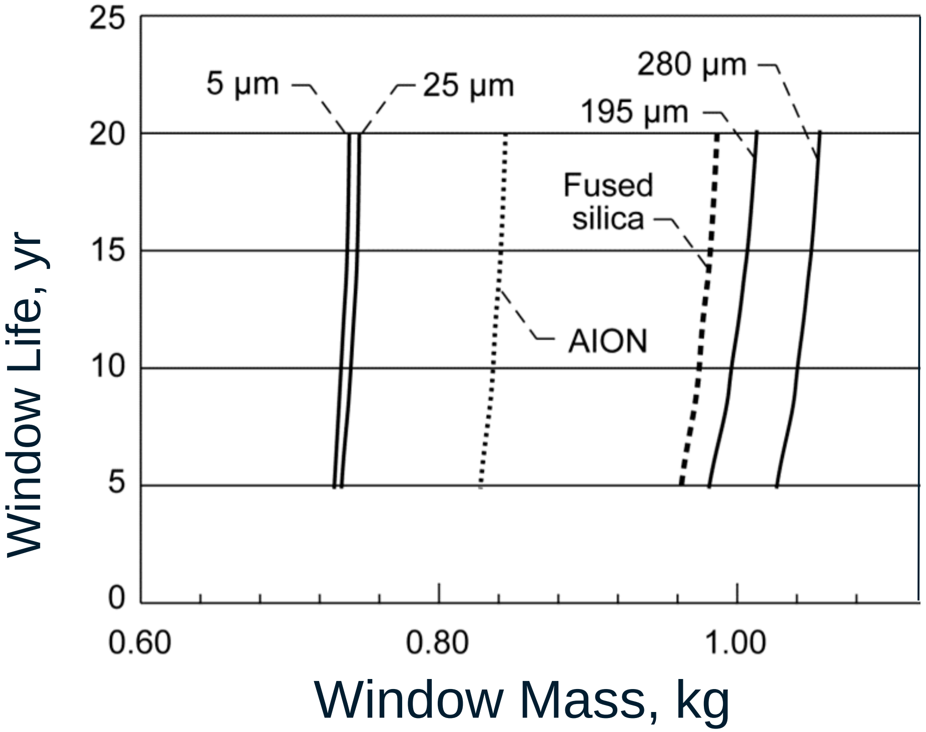
Material	Density (g/cc)	Index of Refraction	Transmission %	Hardness GPa	Young's Modulus (GPa)	Strength MPa	Fracture Toughness (MPa√m)
Strengthened Glass	2.42	1.5	90	6.3	69	~800	0.66
Spinel (coarse grain)	3.6	1.7	~84	16.2	270	80	1.6
Spinel (fine grain)	3.6	----	~88	16	270	160	2.4
AlON	3.7	1.8	~85	18.3	320	210	2.2
Sapphire	3.97	1.8	~88	18.6	380 - 465	400 – 1000	2.1 – 2.5

- Effective fracture toughness due to residual stress > 7 MPa√m!
- Much greater than that of any optical material!!

Relative Mass

- Window mass for a lifetime:

$$m = \left(\frac{t_{f\,min}}{B}\right)^{\frac{1}{2n}} \left(\frac{K_{Ic}}{Y\sqrt{a_{max}}}\right)^{\frac{2-n}{2n}} \left(\frac{3\pi^2 P\rho^2 D^6}{512}(3+\nu)\right)^{\frac{1}{2}}$$



- Yes, mass can be reduced from a SCG Perspective!
- For spinel, the grain size needs to be small……..

Summary

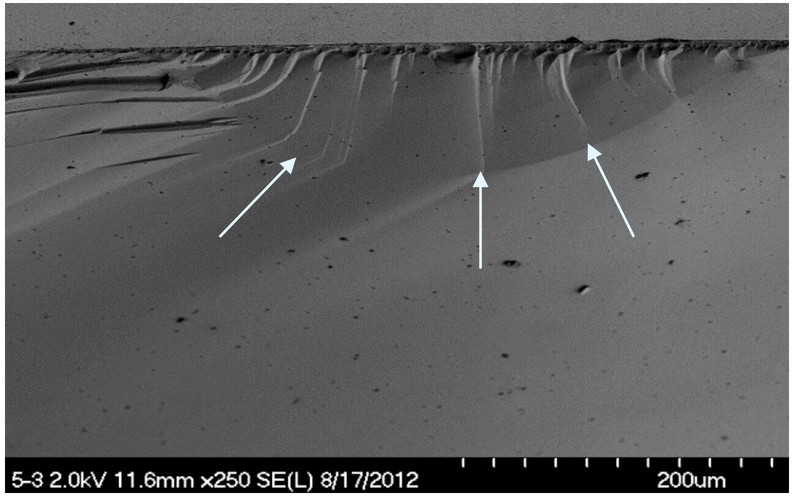
- Spinel and AlON exhibit better fracture toughness and crack growth as compared to glasses, and thus have potential in window systems.
- They can reduce weight from a crack growth perspective.
- Unfortunately, thermal shock resistance metrics are poor - component level testing to qualify.
- Impact size is similar, however, the morphology is very different; residual strength needs to be measured………
- Phone screen applications appear limited due to low effective fracture toughness and refractive index.

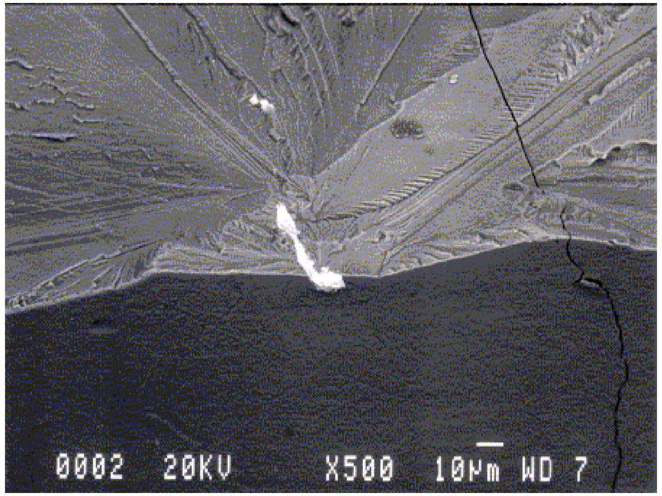
Design Guidelines for Structural Glass and Ceramic Components

Failure Mechanisms

I. Fast (brittle) fracture due over load w/scale effect.

- For glasses and single xtals, occurs from imperfects (scratches, checks, and infrequent pores and inclusions).
- Polycrystals: inclusions, coarse grains, pores and damage.

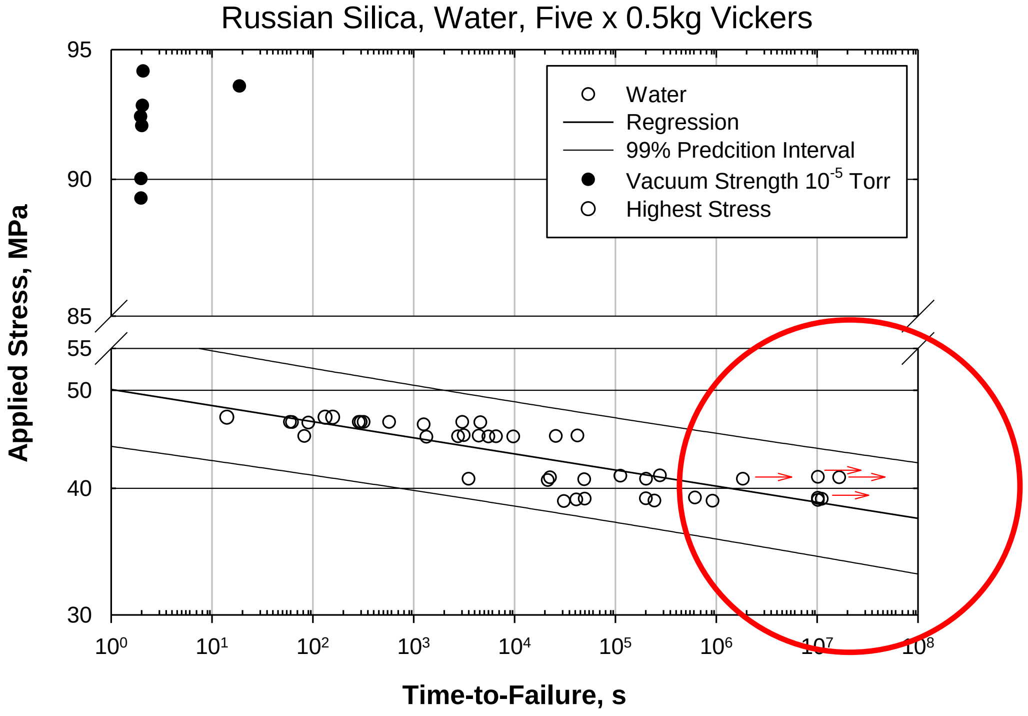


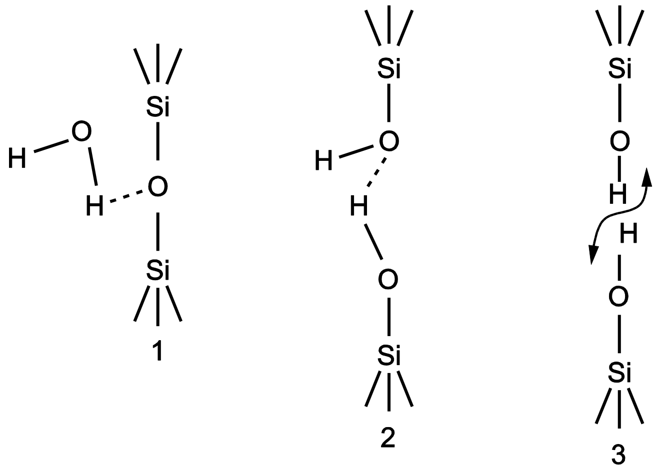


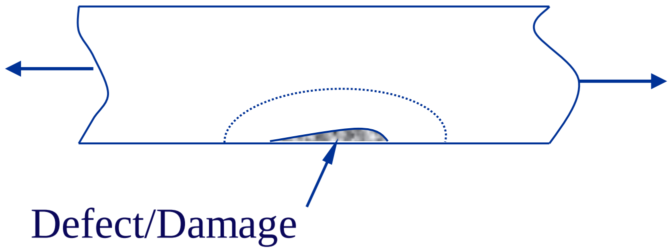
- Damage is surface distributed; pores, etc. are volume distributed.

Failure Mechanisms

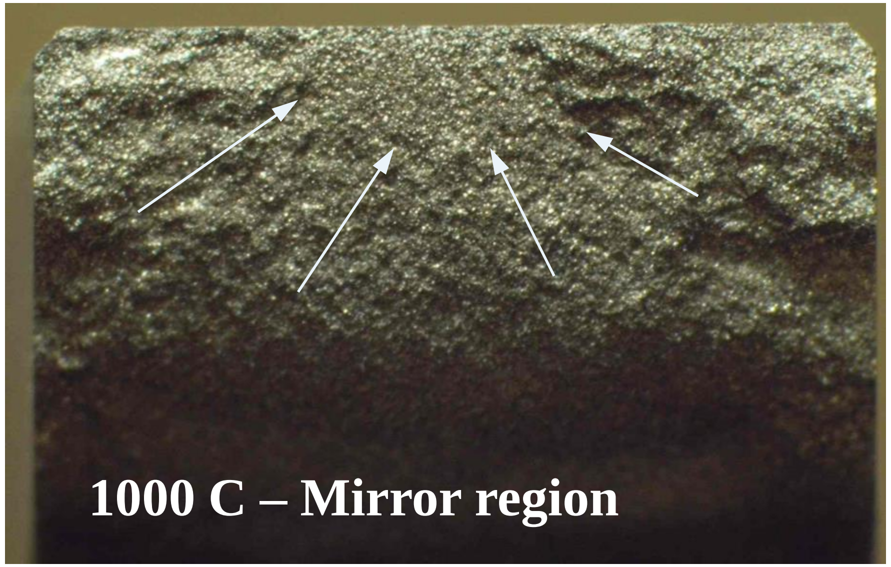
II. Slow crack growth (SCG) or “static fatigue.” Strength decreases with time under static load:

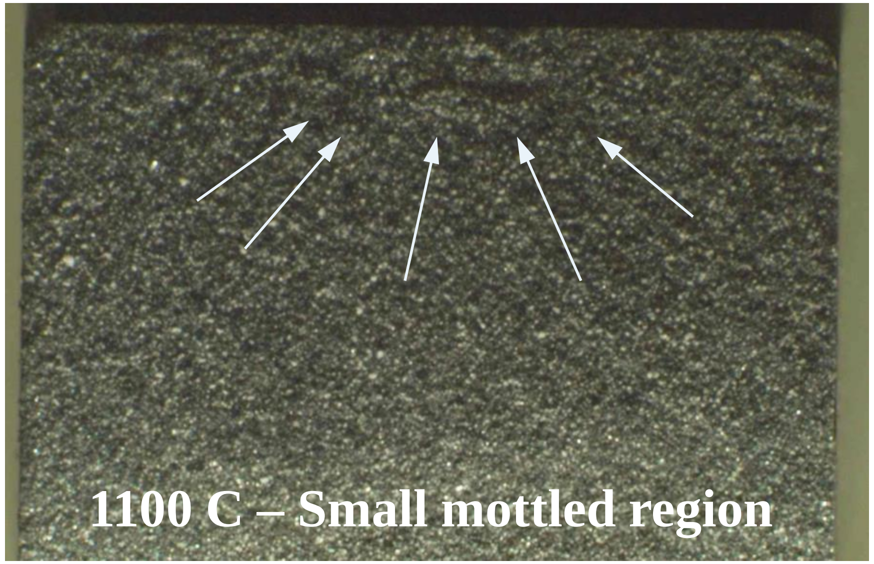


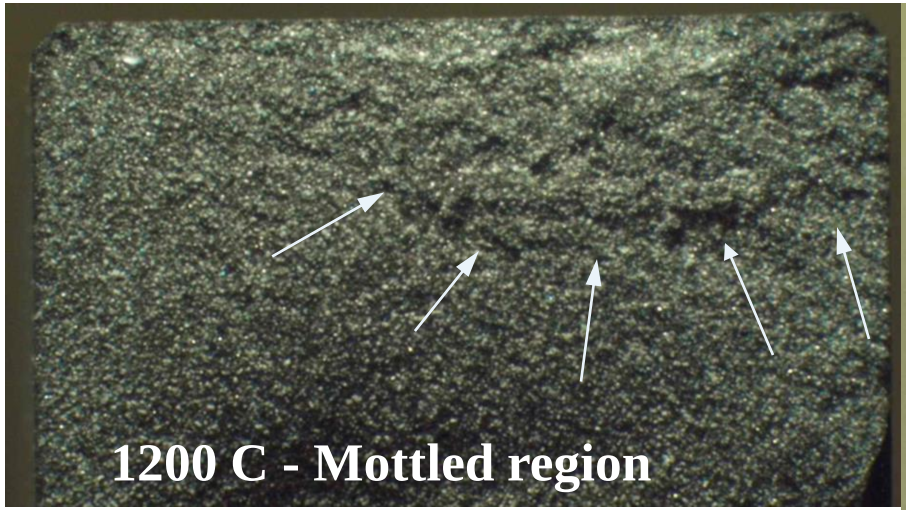


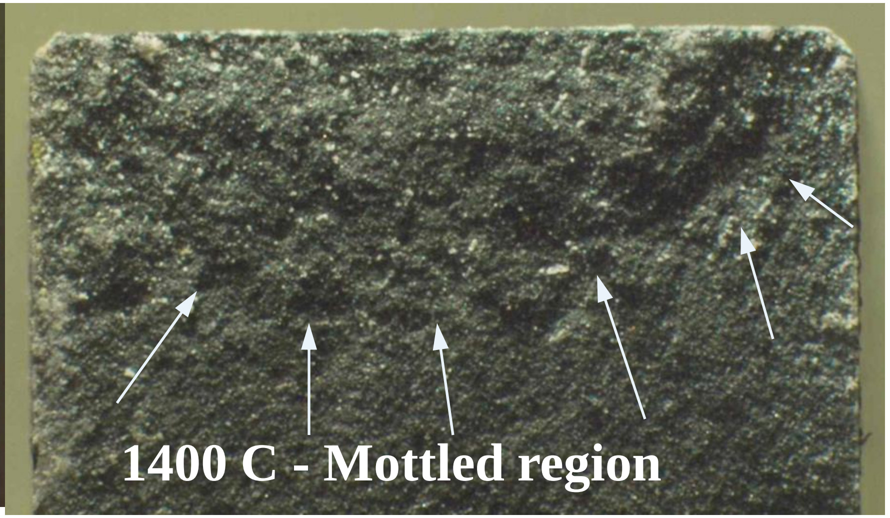


Elevated temperature SCG HfB_2



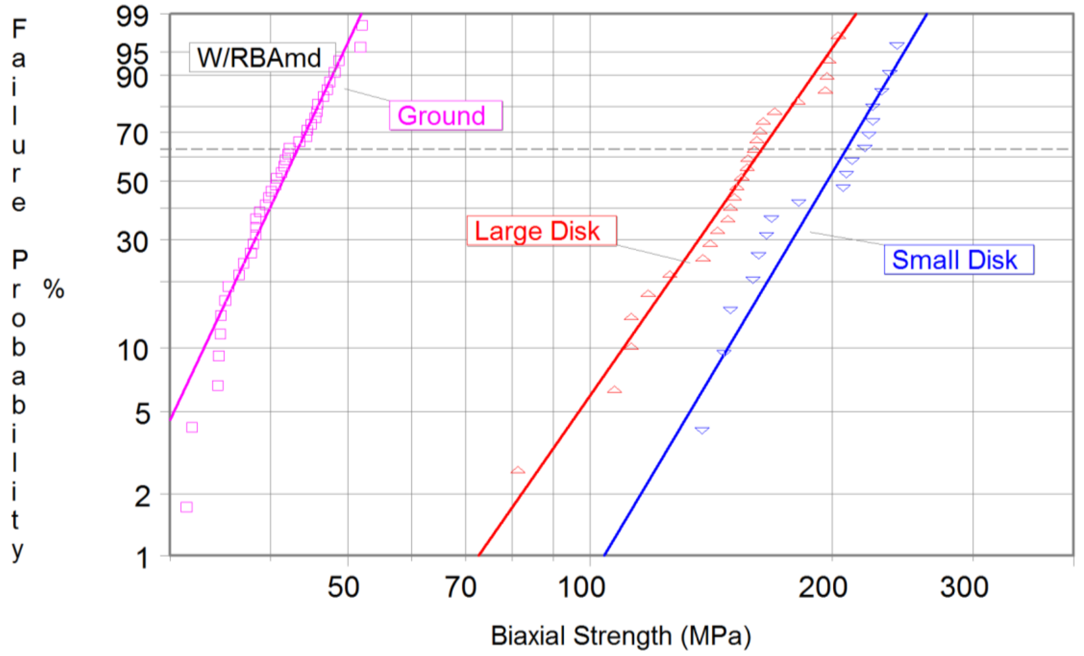






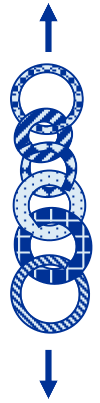
Size Effects and Flaw Populations

- Brittle material without slow crack growth:



Weakest Link Theory:

- Assumes a structure is analogous to a chain with many links; each link may have a different limiting strength
- Catastrophic failure occurs when the weakest link in the chain is broken



- Strength is size dependent. Flaw population can change significantly.

➢ Strength is variable; not the inherent property. *Fracture toughness* is the inherent property: Strength results from the fracture toughness and flaw size present.

Decision Tree

Slow Crack Growth?

No →

Fast Fracture Problem

Weibull distribution

- MOS
- Reliability analysis
- $\sigma < 1$ ksi (glasses)

Yes →

Time Dependent Problem

Slow Crack Growth analysis

- Threshold design
- Transient reliability
- Deterministic SCG
- Very dry environment

$$t_f = B S_I^{n-2} \sigma^{-n}$$

Design Methods

- Margin of Safety:
  - Strength statistics, (m, σ_θ)
  - Factor of safety; close to threshold
  - Doesn't address SCG directly
  - Does not account for scale…..

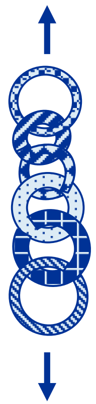
$$MoS = \frac{S_{\theta(B-basis)}}{FOS \cdot \sigma_{pred}} - 1 > 0$$

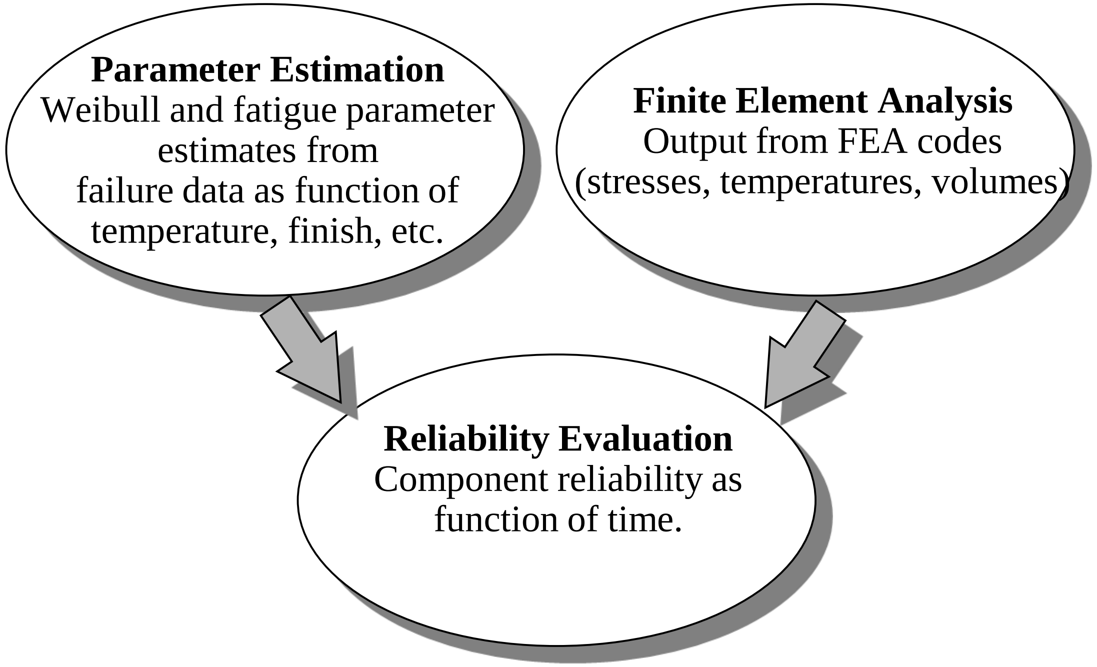
Design Methods

- Weakest Link Theory:
  - CARES/Life: (m, σ_θ , n, B)
  - strength based transient reliability
  - scale effects, multiple flaw populations
  - slow crack growth($v = Ak^n$)

Weakest Link Theory:

- Assumes a structure is analogous to a chain with many links; each link may have a different limiting strength
- Catastrophic failure occurs when the weakest link in the chain is broken





Design Methods

- Deterministic fracture mechanics:
  - NASGRO (m, σ_θ , n, A, K_{Ic})
  - safety factor(s)
  - slow crack growth
  - required for manned

Test Methods

Committee C28 Advanced Ceramic Standards

ASTM INTERNATIONAL

Visit the C28 website (http://www.astm.org/COMMITTEE/C28.htm) to purchase C28 standards or join Committee C28.

Monolithics

C 1161 Flexural Strength (RT)
C 1211 Flexural Strength (HT)
C 1368 Slow Crack Growth (RT, Dyn Fatigue)
C 1465 Slow Crack Growth (HT, Dyn Fatigue)
C 1576 Slow Crack Growth (RT, Stress Rupture)
C 1684 Flexural Strength (Rods)
C 1834 Slow Crack Growth (HT, Stress Rupture)

C 1421 RT Fracture Toughness

C 1322 Fractography
C 1678 Fracture Mirror

C 1424 Compression Strength (RT)

C 1273 Tensile Strength (RT)
C 1291 Creep, Creep Rupture
C 1366 Tensile Strength (HT)
C 1361 Cyclic Fatigue

C 1326 Knoop Hardness
C 1327 Vickers Hardness

C 1499 Biaxial Strength (RT)

C 1198 Elastic Modulus - continuous
C 1259 Elastic Modulus - impulse

k, α, c
C 1470 Thermal Guide

C 1323 C-ring Strength

C 1495 Grinding

ΔT_c
C 1525 Thermal Shock

Composites, Coatings, Porous Ceramics

C 1275 CMC Tensile Strength (RT)
C 1337 Creep, Creep Rupture
C 1359 CMC Tensile Strength (HT)
C 1360 Cyclic Fatigue
C 1773 CMC Tube Axial Tensile (RT)

C 1358 CMC Compression Strength

C 1468 CMC Tensile Strength Trans Thickness

C 1557 Filament Strength & Stiffness

C 1819 Hoop Tensile Strength of CMC tubes (elastomer insert)

C 1469 Joint Strength

C 1341 CMC Flexure Strength
C 1674 Honeycomb Flex Strength

C 1292 CMC Shear Strength (RT)
C 1425 Shear Strength (HT)

C 1624 Coatings – Scratch Adhesion

C 1835 Classification for SiC/SiC
C 1836 Classification for C/C

Powders

d

C 1070 Particle Size, Laser Light
C 1274 Particle Size, BET
C 1282 Particle Size, Centrifugal Sed.

C N O

C 1494 C, N, O in silicon nitride

NDE and Design

99. P_f, % 1. σ
C 1239 Weibull

log S, -1/m, log V_E
C 1683 Weibull Scaling

C 1212 Seeded Voids
C 1336 Seeded Inclusions

C 1175 NDE Guide

C 1331 Ultrasonic Velocity
C 1332 Ultrasonic Attenuation

Terms, Workshops, Education

STP

STP 1201 Life Prediction
STP 1309 Composites
STP 1392 Composites
STP 1409 Fracture

C 1145 Terminology

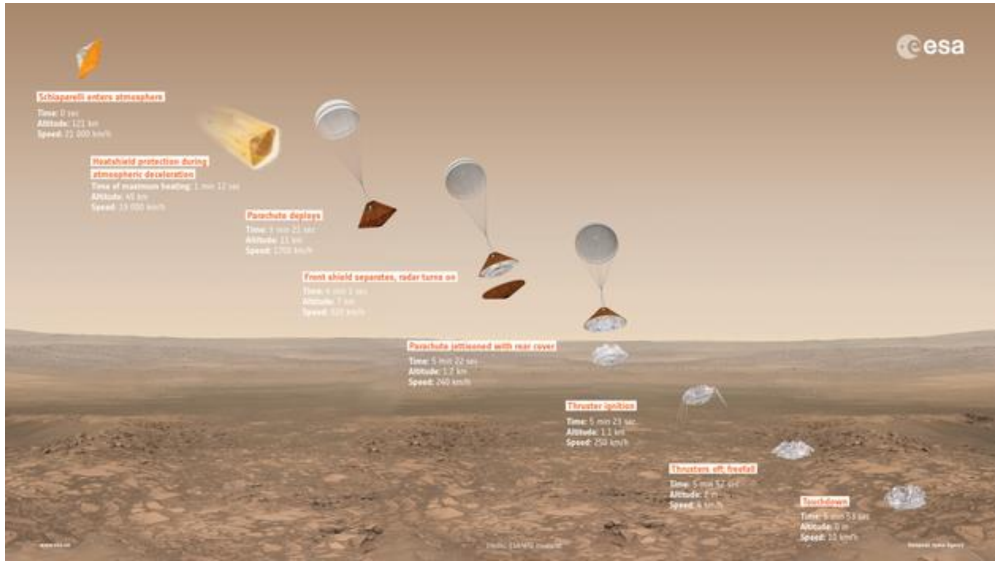
Subcommittees
C28.01 Mech. Prop. + Reliability
C28.03 Physical Prop. + NDE
C28.04 Applications
C28.07 Ceramic Matrix Composites
C28.91 Terminology

ASTM C28 standards are found in Vol. 15.01 of the Annual Book of ASTM Standards

08-2016

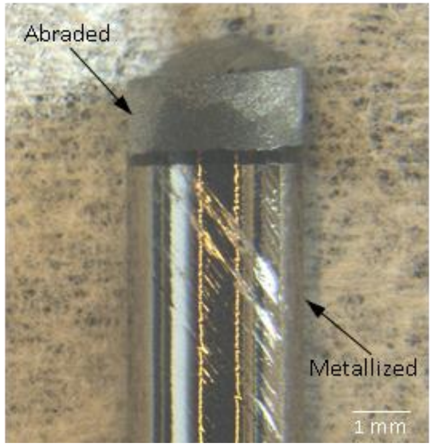
Example – MOMA (Mars Organic Molecule Analyzer)

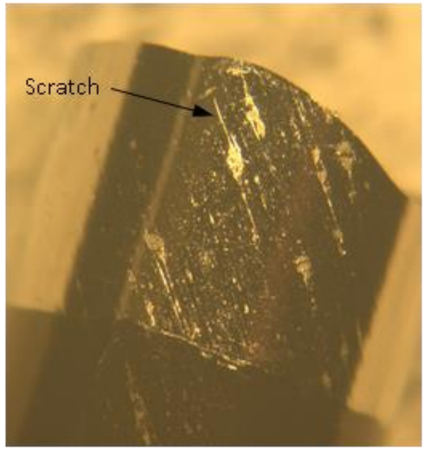
- European Space Agency missions to understand if life ever existed on Mars.
- NASA providing the Mars Organic Molecule Analyzer.



Metal Coated Funnels and Tubes

- What was available:

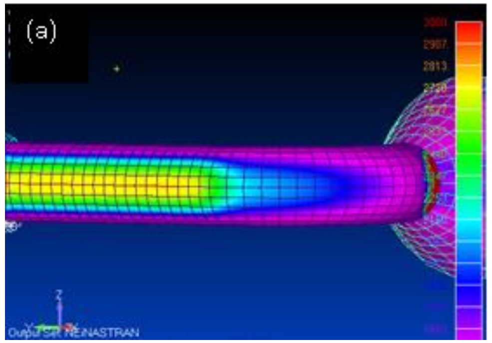


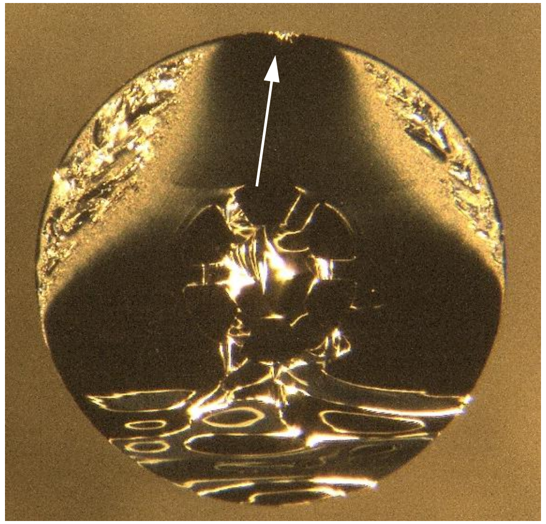


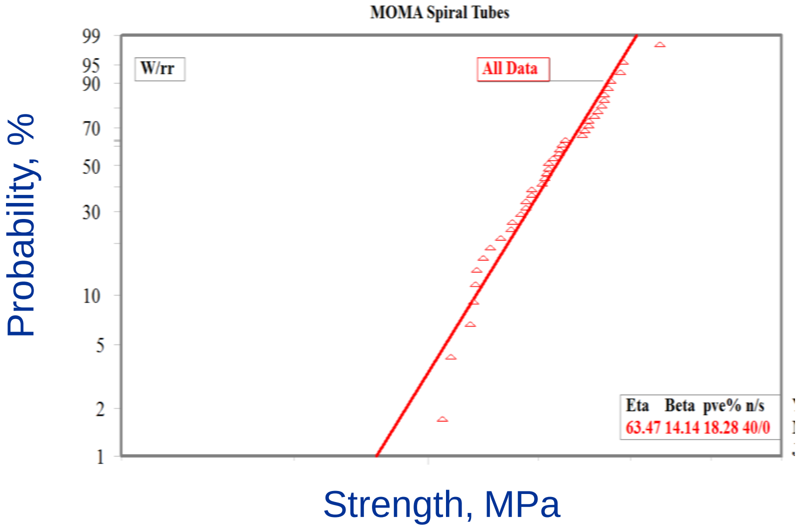
- Component have many surface scratches etc.
- Failure occurs at surface damage.

MOMA Glass Tubes

- Setup non-standard bend test for tubes and funnels:







MOMA Glass Tubes – MoS Analysis

- Stress level w/vibe of 1 ksi
- A-basis strength allowable of 5.8 ksi
- ➢ MoS = 0.9.
- Short load time, dry environment.

Summary

- New materials exhibit better toughness and crack growth characteristics as compared to silica, and thus have potential in window systems. More work is needed to qualify these materials.
- Some applications appear to be limited due to the low effective fracture toughness and optical properties.
- Many testing and design methods have been developed.
- But, the effects of scale and multiple flaw populations need to be considered in the design process.

Acknowledgements

- Thanks to Jim McMahon (JSC) and Penni Dalton (HEMOD) for funding.
- Thanks to Lynda Estes for many discussions.